Search for new physics via CP violation in $B_{d,s} \to l^+l^-$

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Abstract

It is shown that in the approximation of $|\frac{q}{p}|=1$ the CP violation in $B^0_{d,s} \to l^+l^-$ decays vanishes in SM. In a 2HDM with CP violating phases and MSSM the CP asymmetries depend on the parameters of models and can be as large as 40% for B^0_d and 3% for B^0_s. An observation of CP asymmetry in the decays would unambiguously signal the existence of new physics.

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The flavor changing neutral current process, $B_{d,s} \to l^+l^-$ (l=μ, τ), has attracted a lot attention since it is very sensitive to the structure of SM and potential new physics beyond SM and was shown to be powerful to shed light on the existence of new physics before possible new particles are produced at colliders[1, 2, 3]. In a very large region of parameter space supersymmetric(SUSY) contributions were shown to be easy to overwhelm the SM contribution[2, 3, 4] and even reach, e.g., for l=μ, the experimental upper bound[5]

$$B_r(B_d \to \mu^+\mu^-) < 6.8 \times 10^{-7} \quad (CL = 90\%)$$
$$B_r(B_s \to \mu^+\mu^-) < 2.0 \times 10^{-6} \quad (CL = 90\%). \tag{1}$$

In other words measuring the branching ratio of $B_{d,s} \to l^+l^-$ can give stringent constraints on the parameter space of new models beyond SM, especially for that of the minimal supersymmetric standard model (MSSM) because of the $\tan^3\beta$ dependence of SUSY contributions in some large $\tan\beta$ regions of the parameter space[2, 3]. Comparing with hadronic decays of B mesons, this process is very clean and the only nonperturbative quantity involved is the decay constant that can be calculated by using lattice, QCD sum rules etc.

The results on CP violation in B_d - $\bar{B}_d$ mixing have been reported by the BaBar and Belle Collaborations[6] in the ICHEP2000 Conference, which are consistent with the world average[7] . More experiments on B physics have been planned in the present and future B factories [8]. In the letter we study CP violation in $B_{d,s} \to l^+l^-$ (l=μ, τ), which might be measured in the near future.

Obviously for the process $B_{d,s} \to l^+l^-$ there are no direct CP violations since there are no strong phases in the decay amplitude[1, 2, 3]. But it is well known that CP violating

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effects can survive after taking into account the mixing of the neutral mesons, B^0 and $\bar{B}^0$, in the absence of the strong phases. We will give a model-independent description for the CP violating effects of the process induced by mixing of B^0 and $\bar{B}^0$ and analyze them in SM and new models, a two Higgs doublet model(2HDM) with CP violating phases and MSSM.

We need to know what kind of CP violating observables can be defined in the process. At first, direct CP violation, as noted above, is absent in this process. T-odd projection of polarization is a kind of useful tool to probe the CP violating effects, for example, in $B \to X\, l^+ l^-$ [9, 10, 20]. However for the process we are discussing here, we have actually only one independent momentum and one independent spin which can be chosen as those of l^-, so no T-odd projections can be defined. Unlike the case generally discussed for hadronic final states, for example, that in Ref. [11], the detected final states of l^+ and l^- of this process in experiments are basically two asymptotic energy-momentum eigenstates which are not CP eigenstates. Considering for instance B^0 decays to l^+l^- in the rest frame of B^0, due to the energy-momentum conservation we denote the four-momenta of l^- and l^+ as $p = (E, \vec{p})$ and $\bar{p} = (E, -\vec{p})$. Then the angular momentum conservation tells us that $l_L^+ l_R^-$ and $l_R^+ l_L^-$ final states are forbidden. Hence we are left with a pair of CP conjugated final states, $l_L^+ l_L^-$ and $l_R^+ l_R^-$ and two couple of corresponding CP conjugated processes. Therefore, we may define the time dependent CP asymmetries as

$$A_{CP}^1(t) \;=\; \frac{\Gamma(B_{phys}^0(t) \to l_L^+ l_L^-) - \Gamma(\bar{B}_{phys}^0(t) \to l_R^+ l_R^-)}{\Gamma(B_{phys}^0(t) \to l_L^+ l_L^-) + \Gamma(\bar{B}_{phys}^0(t) \to l_R^+ l_R^-)} \tag{2}$$

$$A_{CP}^2(t) \;=\; \frac{\Gamma(B_{phys}^0(t) \to l_R^+ l_R^-) - \Gamma(\bar{B}_{phys}^0(t) \to l_L^+ l_L^-)}{\Gamma(B_{phys}^0(t) \to l_R^+ l_R^-) + \Gamma(\bar{B}_{phys}^0(t) \to l_L^+ l_L^-)} \tag{3}$$

Two corresponding time integrated CP asymmetries are

$$A_{CP}^i \;=\; \frac{\int_0^\infty dt\, \Gamma(B_{phys}^0(t) \to f_i) - \int_0^\infty dt\, \Gamma(\bar{B}_{phys}^0(t) \to \bar{f}_i)}{\int_0^\infty dt\, \Gamma(B_{phys}^0(t) \to f_i) + \int_0^\infty dt\, \Gamma(\bar{B}_{phys}^0(t) \to \bar{f}_i)} \qquad i = 1, 2 \tag{4}$$

Where $f_{1,2} = l_{L,R}^+ l_{L,R}^-$, $\bar{f}$ is the CP conjugated state of f.

The time evolutions of the initial pure B^0 and $\bar{B}^0$ states are given by[14]

$$|B_{phys}^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p} g_-(t)|\bar{B}^0\rangle,$$

$$|\bar{B}_{phys}^0(t)\rangle = \frac{p}{q} g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle. \tag{5}$$

with $g_\pm(t)$ given by

$$g_+(t) = exp(-\frac{1}{2}\Gamma t - imt)cos(\frac{\Delta m}{2}t),$$

$$g_-(t) = exp(-\frac{1}{2}\Gamma t - imt)isin(\frac{\Delta m}{2}t) \tag{6}$$

The absence of strong phases implies

$$|A_f| = |\bar{A}_{\bar{f}}|, \quad |A_{\bar{f}}| = |\bar{A}_f| \tag{7}$$

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where $A_f(\bar{A}_f) = <f|\mathcal{H}_{eff}|B^0(\bar{B}^0)>$. And the CPT invariance leads to

$$\frac{\bar{A}_f}{A_f} = \left(\frac{A_{\bar{f}}}{\bar{A}_{\bar{f}}}\right)^* \tag{8}$$

For simplicity, define

$$\frac{\bar{A}_f}{A_f} = \rho e^{i\phi_f}, \qquad \frac{q}{p} = x e^{i\phi_x}. \tag{9}$$

From Eqs.(2), (3), (5), (7), and (8), it is straightforward to derive

$$r \equiv \left|\frac{A(\bar{B}^0(t) \to \bar{f})}{A(B^0(t) \to f)}\right| = \frac{|1 + x^{-1}\rho tan(\frac{\Delta m}{2}t)exp[i(-\phi_f - \phi_x + \frac{\pi}{2})]|}{|1 + x\rho tan(\frac{\Delta m}{2}t)exp[i(\phi_f + \phi_x + \frac{\pi}{2})]|}. \tag{10}$$

Therefore, if

$$x \neq 1 \tag{11}$$

or

$$\phi_f + \phi_x \neq 0 \quad mod \ \ 2n\pi, \tag{12}$$

(or equivalently $Im(\frac{q}{p}\frac{\bar{A}_f}{A_f}) \neq 0$,) then $r \neq 1$, i.e., one has CP violation.

The effective Hamiltonian governing the process $B_{d,s} \to l^+l^-$ has been given in Refs. [2, 3]. Using the effective Hamiltonian, we obtain by a straightforward calculation [1]

$$\frac{\bar{A}_{f_1}}{A_{f_1}} = -\frac{\lambda_t}{\lambda_t^*}\frac{C_{Q1}\sqrt{1 - 4\hat{m}_l^2} + (C_{Q2} + 2\hat{m}_l C_{10})}{C_{Q1}^*\sqrt{1 - 4\hat{m}_l^2} - (C_{Q2}^* + 2\hat{m}_l C_{10}^*)}, \tag{13}$$

where $\lambda_t = V_{tb}V_{td}^*$ or $V_{tb}V_{ts}^*$, $\hat{m}_l = m_l/m_{B^0}$ and C_i's are understood as Wilson coefficients at m_B scale[12, 13, 15, 2, 3]. Because C_{Q_i}'s are proportional to m_l and C_{10} is independent of m_l it follows from eq. (13) that CP asymmetry in $B_{d,s} \to l^+l^-$ is independent of the mass of the lepton. That is, it is the same for l = electron, muon and tau.

In SM, one has[16][2]

$$\frac{q}{p} = -\frac{M_{12}^*}{|M_{12}|} = -\frac{\lambda_t^*}{\lambda_t}, \tag{14}$$

up to the correction smaller than or equal to order of 10^{-2}, C_{10} is real, $C_{Q_2} = 0$, and C_{Q_1} is negligibly small. So it follows from Eqs.(13), (14) that $x = 1$ and $\phi_f + \phi_x = 0$. Therefore, there is no CP violation in SM. [3] If one includes the correction smaller than order of 10^{-2}

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[1] We have neglected the contributions, which is smaller than or equal to 10^{-3} of the leading term, from the penguin diagrams with c and u quarks in the loop. It is true for both B_d and B_s decays[17]. Therefore, although there are weak phases from the c or u quark in the loop, in particular, for B_d, the effect on the decay phase induced by them is neglegiblly small.

[2] Note that the phase convention between B^0 and $\bar{B}^0$ is fixed as $\mathcal{CP}|B^0> = -|\bar{B}^0>$ when deriving eqs. (13), (14).

[3] One can check by combining Eqs. (14) and (13) that all freedoms of phase conventions are canceled out completely in $\frac{q}{p}\frac{\bar{A}_{f_1}}{A_{f_1}}$, including the one between B^0 and $\bar{B}^0$.

to $x=1$[4] one will have CP violation of order of 10^{-3} for B_d^0 and 10^{-4} for B_s^0 which are unobservably small.

In the models where Eq. (14) is valid, defining $\xi = \frac{\bar{A}_{f_1}}{A_{f_1}}$, $\bar{\xi} = \frac{q}{p}\xi$ and using Eqs. (8), (14), the time dependent CP asymmetries Eqs. (2) and (3) and time integrated CP asymmetries Eq. (4) can be greatly simplified

$$A_{CP}^1(t) = -\frac{sin(\Delta mt)Im(\bar{\xi})}{cos^2(\frac{1}{2}\Delta mt) + |\xi|^2 sin^2(\frac{1}{2}\Delta mt)} \tag{15}$$

$$A_{CP}^2(t) = -\frac{sin(\Delta mt)Im(\bar{\xi})}{|\xi|^2 cos^2(\frac{1}{2}\Delta mt) + sin^2(\frac{1}{2}\Delta mt)} \tag{16}$$

$$A_{CP}^1 = -\frac{2Im(\bar{\xi})X_q}{(2 + X_q^2) + X_q^2|\xi|^2} \tag{17}$$

$$A_{CP}^2 = -\frac{2Im(\bar{\xi})X_q}{(2 + X_q^2)|\xi|^2 + X_q^2} \tag{18}$$

where $X_q = \frac{\Delta m_q}{\Gamma}$ ($q = d, s$ for B_d^0 and B_s^0 respectively). As expected, they are nonzero in the presence of CP violating phases.

We have discussed the CP asymmetries assuming that B^0 or $\bar{B}^0$ mesons are tagged before the decay $B_q^0 \to l^+l^-$ ($q = d, s$) happen [5] Likewise one may also define CP asymmetries of the opposite tagging order[11] which turn out to be just of the opposite sign of those defined above, (17) and (18). (Eqs. (15) and (16) hold for either tagging order.) The CP asymmetries not requiring measurement of the time order as one may naively imagine to define, however, turn out to be zero because of the the relation Eq. (8) and the approximation Eq. (14) we have used in our discussions.

From Eq. (17) and (18) one can simply get the maximal limit of the CP violating observables

$$|A_{CP}^{1,2}(B_q^0)|_{max} = \frac{1}{\sqrt{2 + X_q^2}} \tag{19}$$

which is about 63% for q=d and 5% for q=s. For B_s^0 we know that X_s is experimentally larger than 15.7(90% CL)[5], so we can neglect the number 2 in the formula and get

$$A_{CP}^2(B_s^0) \doteq -\frac{2Im(\bar{\xi})X_s}{X_s^2|\xi_s|^2 + X_s^2} \doteq A_{CP}^1(B_s^0).$$

The situation is clearly quite different for B_d^0 because X_d is just about 0.73. The two CP asymmetries for B_d^0 do not exhibit strong correlation.

In Fig. 1 the correlation between the CP asymmetries of B_s^0 and B_d^0 is plotted scanning the parameter space of C_{Q_1} and C_{Q_2} with $|C_{Q_i}| \geq 0.1$ ($i = 1, 2$). The points in the figure are plotted satisfying the constraints Eq. (1). One sees that they do not exhibit strong

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[4]According to the box diagram calculation in SM, the deviation of x from 1 is $\sim 10^{-3}(10^{-5})$ for $B_d(B_s)$[16]. So 10^{-2} is a conservative estimate.

[5]An analysis of tagging has been carried out in Refs.[18, 11].

correlation in the parameter space which is actually implied by the fact that in the most of the parameter space, $|\xi_s|^2$ (of order one) is not important at all because of the very large X_s^2, while $|\xi_d|^2$ would compete with X_d^2 in the formula Eq. (17).

We now discuss CP violation of the process in a general 2HDM and MSSM. It has been shown [19] that the contributions to the mixing of B^0 and $\bar{B}^0$ from 2HDM or MSSM can be significant when the charged Higgs boson mass and tanβ are small($m_{H^\pm} \leq 200$ GeV and tan$\beta \sim 2$) or the gluino mass and the squark mass are small (around 100 GeV and 200 GeV respectively) and tanβ is also small. While all other contributions suppressed in the large tanβ limit, the only contribution surviving in this limit is the contribution coming from exchanging neutrilino and down-type squarks and the contribution can become important only in a very narrow region of down-type squark mass in the low mass spectrum case[19]. In the following we limit ourself to discuss CP violation for B^0 and $\bar{B}^0$ decays far away from these regions, i.e., in the regions with large tanβ and relatively heavier down-type squark mass. Therefore, to a good approximation we can take the mixing to be that in SM, i.e., Eq.(14). Thus we can use Eqs. (15), (16), (17) and (18) in the numerical analysis. The explicit expressions of the Wilson coefficients C_{10}, C_{Q_1}, C_{Q_2} in a CP softly broken 2HDM and MSSM can be found in Refs.[20, 2].

For a CP softly broken 2HDM[20], the CP violation is depicted by the phase of vacuum ξ_H (i.e., ξ in Ref. [20]). In Fig. 2 we give the plots of A_{CP}^2 for B_d^0 as functions of ξ_H varying between $[0, 2\pi]$. Other parameters describing the model are chosen as $M_{H1} = 120\ GeV$, $M_{H2} = M_{H^\pm} = 200\ GeV$, tan$\beta = 50$ for which the experimental constraints of $K - \bar{K}$ and $B - \bar{B}$ mixing , $\Gamma(b \to s\gamma)$, $\Gamma(b \to c\tau\bar{\nu}_\tau)$ and R_b are well satisfied. The constraints of electric dipole moments (EDMs) of the electron and neutron are also satisfied except for $\xi_H = \frac{\pi}{4}$[20]. One may find that the CP asymmetry can be as large as 20% in vast of the range of ξ_H and can even reach 50%. For B_s^0, the dependence of the CP asymmetry on ξ_H is similar to that for B_d^0 and the CP asymmetry can reach 3%.

For generic SUSY models, the constraints from the EDMs of the electron and neutron on the CP violating phases have been analyzed by many authors[21, 10]. The scenario with large tanβ, which we are interested in here, have been discussed in our previous papers[10]. The constraint of $B \to X_s\gamma$ has also been presented there. In the case of low mass spectrum (the lighter stop of order 200 GeV and chargino masses less than 200 GeV), C_{Q1} and C_{Q2} are constrained by the $B \to X_s\gamma$ decay, because C_{Q_i} and C_7 (the branching ratio of $b \to s\gamma$ is determined by $|C_7|^2$) both receive most important SUSY contributions from exchanging top squark. An interesting case happens when the SM contribution to C_7 is completely canceled by the real part of SUSY contributions and a considerable imaginary part is left[10] (so that the constraint on C_7 is satisfied) if tanβ is large enough (say, ≥ 30). C_{Q1} and C_{Q2}, in this case, exhibit phases about $\pm\pi/4$ and consequently the absolute value of CP asymmetries for B_d^0 can be significantly larger than 30%. CP asymmetries for B_s^0 can also be $\pm3\%$ in this case. As pointed out in Ref.[10], the above areas of parameter space are allowed by the EDM constraints due to the cancellation among the various contributions to EDMs. For the case of high mass spectrum where the $B \to X_s\gamma$ constraint can be safely satisfied and the CP violating phases of trilinear term, A_t, and μ can survive in almost all of their parameter space after satisfying the constraints of electron and neutron EDMs, the magnitudes of C_{Q1} and C_{Q2} are also suppressed by the mass spectrum and CP asymmetries can exhibit the

correlation depicted in Fig. 1. But for this scenario the branching ratio of the decay would not be enhanced large enough, so it is less interesting. In the supergravity(SUGRA) model there is another feature which would have important phenomenological implications, i.e., because electroweak (EW) symmetry is broken spontaneously by the radiative breaking mechanism the masses of the two heavier neutral Higgs bosons are of the same order. Hence in general there is a large cancellation happened in the numerator of Eq. (13) in SUGRA models. The consequence of it is that for B_d^0, A_{CP}^1 is greatly suppressed(see Eq. (17)) even in the case of low mass spectrum and the two CP asymmetries for B_s^0 are both small ($< 10^{-2}$).

With the branching ratios $Br(B_q^0 \to l_L^+ l_L^-)$ and $Br(B_q^0 \to l_R^+ l_R^-)$ given respectively by

$$C_{B_q^0} \times \left[(1 - 4\hat{m}_l^2)|C_{Q_1}|^2 + |C_{Q_2} + 2\hat{m}_l C_9|^2 - 2\sqrt{1 - 4\hat{m}_l^2}[C_{Q1}^* \times (C_{Q2}2 + \hat{m}_l C_9) + h.c.] \right]$$
(20)

and

$$C_{B_q^0} \times \left[(1 - 4\hat{m}_l^2)|C_{Q_1}|^2 + |C_{Q_2} + 2\hat{m}_l C_9|^2 + 2\sqrt{1 - 4\hat{m}_l^2}[C_{Q1}^* \times (C_{Q2} + 2\hat{m}_l C_9) + h.c.] \right]$$

where

$$C_{B_q^0} = \frac{G_F^2 \alpha_{EM}^2}{64\pi^3} m_{B_q^0}^3 \tau_{B_q^0} f_{B_q^0}^2 |\lambda_t|^2 \sqrt{1 - 4\hat{m}_l^2},$$

we calculate the events N_q^i (i=1,2) needed for observing A_{CP}^i at 1σ in the areas of parameter space in which A_{CP}^i and the branching ratios both have large values and all experimental constraints are satisfied. For l=μ, they are order of 10^8 and 10^9 for B_d^0 and B_s^0 respectively in 2HDM with CP violating phase and tanβ=50 or in SUSY with tanβ=30 as well as sparticle masses in a reasonable range. Therefore, 10^{10} (10^{11}) B_d (B_s) per year, which is in the designed range in the future B factors with 10^8- 10^{12} B hadrons per year [23], is needed in order to observe the CP asymmetry in $B \to \mu^+\mu^-$ with good accuracy. For l=τ, the events N_q^i are order of 10^6 and 10^7 for B_d^0 and B_s^0 respectively in 2HDM with CP violating phase and tanβ=50 or in SUSY with tanβ=30 as well as sparticle masses in a reasonable range. Assuming a total of $5 \times 10^8(10^9)$ $B_d\bar{B}_d$ ($B_s\bar{B}_s$) decays, one can expect to observe $\sim$ 100 identified $B_q \to \tau^+\tau^-$ events, permitting a test of the predicted CP asymmetry with good accuracy.

As discussed above, we need to seperate the final state $l_L^+ l_L^-$ from $l_R^+ l_R^-$ in order to measure CP asymmetry. For l=τ, the polarization analysis is straightforward. However, detecting tau's is difficult experimentally. For l=μ, in principle one can separate the final state $\mu_L^+\mu_L^-$ from $\mu_R^+\mu_R^-$ by measuring the energy spectra of the electron from muon decay[22]. A μ_L will decay to an energetic e_L, which must go forward to carry the muon spin, and a less energetic pair of neutrino and antineutrino because the electron is always left-handed[6] and the energy-momentum and angular momentum are conserved. Due to the same reason, for μ_R, the relative energies of electron and a pair of neutrino and antineutrino are roughly reversed. Therefore, the energy spectra of the electron from

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[6]In the present case it is quite a good approximation to ignore the mass of electron.

muon decay is a powerful μ spin analyzer. However, in practice muons never decay in a 4π detector because the lifetime of a muon is long ($c\tau$=659 m). A possible way to measure a polarized muon decay is to build special detectors which can make muons lose its energy but keep polarization so that the polarized muon decays can be measured.

In summary, we have analyzed the CP violation in decays $B_q^0 \to l^+l^-$ (q=d,s). While there is no direct CP violation, there might be mixed CP violation in the process

$$B^0 \to \bar{B}^0 \to f \qquad vs. \qquad \bar{B}^0 \to B^0 \to \bar{f}. \tag{21}$$

It is shown that in the approximation of $|\frac{q}{p}|$=1 the CP violation vanishes in SM. If including the correction of order of 10^{-2} to $|\frac{q}{p}|$=1, CP violation is smaller than or equal to $O(10^{-3})$ which is unobservably small. In a 2HDM with CP violating phases and MSSM the CP asymmetries depend on the parameters of models and can be as large as 40% for B_d^0 and 3% for B_s^0. Therefore, an observation of CP asymmetry in the decays $B_q^0 \to l^+l^-(q = d, s)$ would unambiguously signal the existence of new physics.

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Figure Captions

Fig. 1 The correlation between CP asymmetries for B_d^0 and B_s^0.

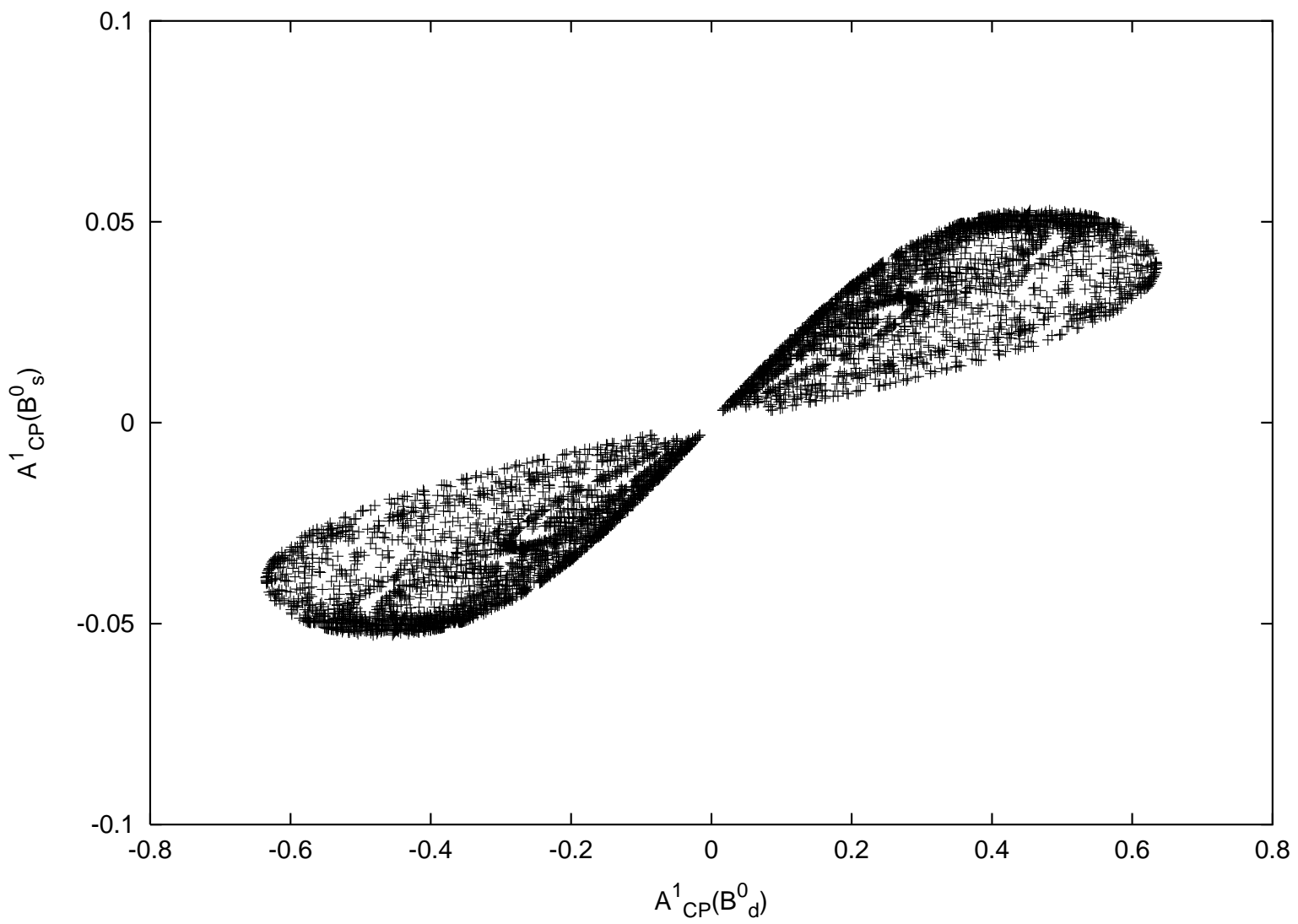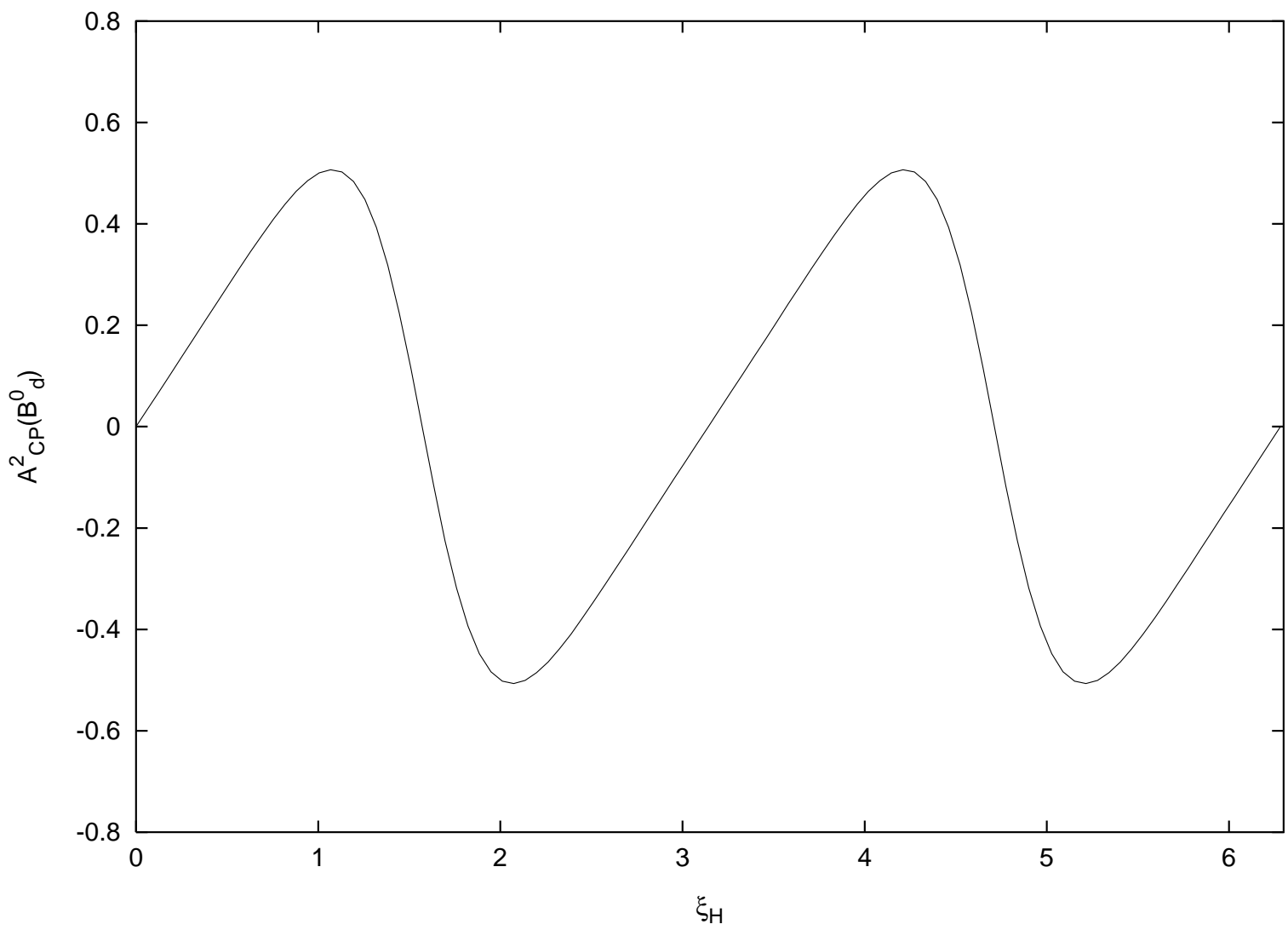Fig. 2 A_{CP}^2 for B_d^0 versus the CP violating phase ξ_H in 2HDM.

Figure 1:

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Figure 2: